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Aquarius Mountain Area, Arizona: A Possible HDR Prospect

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AQUARIUS MOUNTAIN AREA, ARIZONA: A POSSIBLE HDR PROSPECT

by

F. G. West and A. W. Laughlin

ABSTRACT

Exploration for Hot Dry Rock (HDR) requires the ability to delineate areas of thermal enhancement. It is likely that some of these areas will exhibit various sorts of anomalous conditions such as seismic transmission delays, low seismic velocities, high attenuation of seismic waves, high electrical conductivity in the crust, and a relatively shallow depth to Curie point of magnetization. The Aquarius Mountain area of north-west Arizona exhibits all of these anomalies. The area is also a regional Bouguer gravity low, which may indicate the presence of high silica type rocks that often have high rates of radioactive heat generation. The one deficiency of the area as a HDR prospect is the lack of a thermal insulating blanket.

I. INTRODUCTION

The first step in any type of resource exploration program, geothermal included, is the development of an exploration philosophy.¹ Various factors such as program objectives, economics, and resource characteristics will shape the exploration plan. Economic factors include grade and size of the deposit, proximity, and type of user. To date, factors other than the resource characteristics have controlled the philosophy of exploration in the Hot Dry Rock (HDR) program. This report will examine one approach to HDR exploration, an approach based primarily on the resource characteristics of HDR.

HDR is a generally pervasive resource at depth and is found at moderately shallow depths in certain thermally enhanced areas. Previous deliberations on potential HDR sites have concentrated on high-grade thermal areas that have surface manifestations, such as hot springs or young volcanism. The locations of these obvious high potential source areas are well known, many appearing on road maps. Unfortunately many, or perhaps most, of these sites lie in unpopulated regions or within national parks or monuments, thus precluding any direct utilization or dictating their use solely for electrical generation. Discovery of thermally enhanced areas near to users requires a somewhat more sophisticated program than merely locating seeps. There is good reason to believe that the geologic, geophysical, and geochemical techniques exist that will allow the necessary detection and evaluation of masked thermal resources.

Some element of contradiction obviously exists between the statement that HDR is a pervasive resource at depth and the suggestion that one must explore for HDR. This conflict is generated by the economic considerations of utilizing the highest grade thermal source in spite of remote location and the ensuing realization that using this source is often the least efficient utilization of the energy resource or of limited institutional resources such as men, material, and money. The most efficient use of thermal resources would be from a source directly under a user. Again this may not be the most efficient use of institutional resources. The most efficient utilization of all resources will most likely be at a site of intermediate thermal grade relatively near a user. Therefore, one must have the capability of selecting the highest grade site with reference to a particular user such that the utilization of all resources will be maximized. To accomplish this, one not only must believe that the necessary exploration methods are available but must have demonstrated their success.

II. HDR EXPLORATION TECHNIQUES

A. Geological

Various geological processes occurring singly or in combination result in the thermal enhancement of a region. A regional scale of enhancement implies that a deep-seated source or process is required to account for the wide distribution. Some of these procedures are: emplacement of hot material (magma, water, or both?) in the crust, enrichment of the content of radioactive heat-producing elements, release of heat by exothermic chemical reactions, and generation of heat

by friction during tectonic activity. The distribution of these sources can often be correlated with trends or zones² of weakness in the crust, which have been active more than once in the geologic past.³ Dating the age and sequence of the events producing the enhancement will give insight as to the likelihood for a recent or current thermal enhancement. Delineating these zones can provide a map of potential enhanced thermal areas that can be referenced to potential geothermal users. Geochemical thermometry and tectonic analysis including the analysis of aerial photos are particularly useful in defining these zones.

B. Geophysical

Anomalous physical parameters associated with regional-scaled thermal enhancement are usually rather subtle and require investigation on at least the same scale as the area of enhancement. Various physical properties are known to vary with temperature, some of these are: electrical conductivity, seismic velocity, seismic impedance, and magnetization. Maps of the variation of these properties can provide information on temperature at depth. Gravity maps of a region give insight about the distribution of rock types. Although any one of a variety of geophysical techniques can be used to map a physical property that may give an indication of possible thermal enhancement, greater confidence in the conclusion is provided through confirmation by one or more of the other techniques. A large body of literature indicates that it is feasible to delineate regions or provinces with thermal enhancement.

III. PROSPECT SELECTION

Published or otherwise available regional-scaled investigations, appropriate for use in an HDR exploration program, are rather limited in number. Recent work, however, has indicated several geophysically anomalous areas that appear to be thermally enhanced. Our selection of an area in which to apply and test the thesis that hidden areas of thermal enhancement can be located, using various geologic and geophysical techniques, began with a paper by Carlos Aiken.⁴ This paper, which will be relied on heavily in this report, indicated that a correlation exists in northwest Arizona between regionally corrected residual Bouguer gravity and other geophysical characteristics, such as heat flow. Additional correlations have been found in more recent works.

IV. LOCATION

The core of the anomaly detected by Aiken in northwest Arizona covers an area of about 700 km² in the transitional, or Mexican highland, section of the Colorado Plateau physiographic province between Flagstaff, Prescott, and Kingman. Several landmarks exist in the area (Picacho Butte, Tin Mountain, Cross Mountain, and Mahon Mountains), but the Aquarius Mountains seem to be the most appropriate place name for the "Aiken" anomaly.

V. GEOLOGIC CHARACTERISTICS

The prospect area has received relatively little attention from geologic investigators. This partly reflects the inaccessibility of the region and the apparent dearth of economic mineral deposits. The inaccessibility can be attributed to extreme erosion of the uplift, which occurred in the area in premiddle Miocene time.⁵ The significance of the relative absence of mineral deposits in an area, roughly correlative with the Aiken⁴ gravity low, remains obscure at this time. It has been observed that a general relationship exists between heat flow and the period of time since the last tectonic activity.⁶ This would suggest that the area of uplift, the Tonto physiographic section, should be an area of above normal heat flow. Unfortunately, no heat flow data is available at this time.

The uplift of the northwest-trending Tonto section is shown on northeast-southwest cross sections⁷ (Figs. 1-4). The down faulting on the western side of the area is regarded as the onset of Basin and Range tectonics. The relationship of the prospect area to the northwest trending Texas lineament (Fig. 5) with its left lateral strike slip movement,⁸ the Cordilleran Orogenic Belt with thrust and reverse faulting,⁹ or the north trending Intermountain Seismic Belt of normal and strike slip faulting¹⁰ is unclear. Even less clear is the influence of other tectonic elements inferred to exist in the deep Precambrian basement, such as the Colorado lineament¹¹ and the Murray fracture zone.¹² Economic geologists have generally established, however, that often the thermal enhancement and subsequent mineralization of an area is affected by the upward leakage of fluids near the intersection of large-scale fracture systems.¹³ Unfortunately, for the development of hydrothermal systems, this thermal leakage is a degenerative process in that it tends to seal the fracture permeability necessary for the transport of thermal fluids, unless the permeability is rejuvenated by tectonic

Fig. 1.
Location of northeast-southwest
geologic cross sections.

Fig. 2.
Northeast-southwest cross section A-A'.

Fig. 3.
Northeast-southwest cross
section B-B'.

Fig. 4.
Northeast-southwest cross
section C-C'.

activity.¹⁴ That the area has been tectonically active in the past is evidenced by the silicic volcanic domes,¹⁵ the silicic caldera of the Aquarius Mountains, and the basaltic Mahon Mountain volcano. It has been observed that the locations of the volcanic eruptive centers in the region are controlled by faults.¹⁶ Many of these faults were first active in Precambrian time.¹⁶

VI. GEOPHYSICAL CHARACTERISTICS

A. Gravity

Residual Bouguer gravity values computed for Arizona,⁴ show that a regional scaled gravity low exists in the northwest part of the state. (See Fig. 6 Note: the -30 milligal contour will appear on all other maps for correlation purposes.) Gravity lows can often be interpreted as indicating the presence of low density silicic rock.^{17, 18} The aerial extent of this anomaly suggests that it has dimensions on the order of the thickness of the crust (30-40 km). Emplacement at depth of low-density silicic rocks, which often have a relatively high thermal conductivity and a high heat generation value, should enhance the heat flow. Numerous correlations have been made between high terrestrial heat flow and negative Bouguer anomalies.^{19, 20}

Most of the comments mentioned above are manifested as trends or grain on the gravity map.

Fig. 5.
Major structural lineaments
in Arizona.

Fig. 6.
Residual Bouguer gravity map of
Arizona (modified from Aiken⁴).

B. Geoelectromagnetic

Various authors have discussed the possible use of transients in electric and/or magnetic fields to map electrically conductive structures to great depths.^{21, 22} A number of these studies show correlations with high terrestrial heat flow,²³⁻⁵⁰ which suggest the mapping of lateral variation in crustal electrical conductivity may be useful as a potential method for determining the temperature pattern at depth. Unfortunately, few geoelectromagnetic maps exist. Figure 7 shows an inferred deep-seated electrical conductor underlying the Wasatch geothermal province, which trends south toward the Aquarius prospect.

C. Seismic

Various parameters affecting the transmission of seismic waves have been correlated with temperature.⁵¹ For example, travel time differences of P and S waves in certain areas have been explained by differences in mantle temperature.^{52, 53} The delay times for the region are shown in Fig. 8. The Pn velocity of waves traveling in the upper mantle tends to reflect the thickness of the crust; it is low where the crust is thin and high where it is thick.⁵⁴ The Pn velocity map⁵⁵ for the area is shown in Fig. 9. Attenuation of seismic waves suggests that large parts of the upper mantle are partially melted,⁵⁶ and the anelasticity of the partially melted zone is believed to account for the low seismic velocity of the zone.⁵⁷ Figure 10 shows the seismic attenuation map⁵⁸ for the region. A seismic wave attenuator underlies the Aquarius prospect and continues north into the Wasatch geothermal province, tracing the line mentioned above as an electrical conductor.

The seismicity of an area is of particular importance to HDR development, because seismic activity tends to open fractures in the rock, causing the rock to become permeable. The seismic activity of the prospect area⁵⁹ is shown in Fig. 11. The prospect appears to be something of an aseismic island, surrounded by moderate seismic activity. This peculiar situation suggests some sort of differential motion or environment between the prospect area and the surrounding region. Whether this is related to the negative Bouguer gravity anomaly, the thin crust, the attenuation of seismic waves, the deep-seated electrical conductor, or all of these anomalies will await determination by further field work and a more detailed analysis.

Fig. 7.
Contours of the vertical magnetic component ranges in gamma for a daily variation (modified from Reitzel et al., 1970).

Fig. 8.
Seismic P-wave delay times in seconds (modified from Hales and Herrin, 1972).

Fig. 9.
Variation of Pn velocity (modified from Hales and Herrin, 1972).

Fig. 10.
Contours of longitudinal wave attenuation values for Kazakh event (modified from Jordan et al., 1965).

D. Aeromagnetic

The residual aeromagnetic map of Arizona⁶⁰ exhibits several distinct trends of magnetic highs and lows as shown in Fig. 12. These trends appear to correlate with structural zones or lineaments shown in Fig. 5, particularly with the so-called Colorado and Texas lineaments. Several of the magnetic trends correlate with trends in gravity, thus providing further insight into the distribution of type of rock.

It is possible to infer something of the geothermal potential of an area by using the aeromagnetic data to estimate the depth to the Curie point ($\sim 550^{\circ}\text{C}$) isotherm.⁶¹ The depth to Curie point⁶² is shown in Fig. 13. It appears that an east-west zone of crustal thinning traverses north-central Arizona. This thinning correlated dramatically with the seismic indications of thermal enhancement. The gravity anomaly is generally within the trend of shallow depth to Curie point. To some extent, the grain and outlines of the larger depth to Curie point anomalies correlate with anomalies on the gravity map. The depth to Curie point suggests that the Colorado Plateau begins east of the uplifted transitional zone.⁶³

E. Geothermal Gradient

The preliminary geothermal gradient map for Arizona⁶⁴ is shown in Fig. 14. The contours are based on relatively sparse data; however, known geothermal areas in the state can be used as a base and for control. This map correlates somewhat with the map of gravity the gravity lows correlating with high geothermal gradient and gravity highs with low geothermal gradient. Heat flow data are too sparse to contour in detail, but appear to have some of the same features of the physiographic province map. This indicates that the region and the area of the anomaly has a heat flow of at least 1.5 to 2.0 heat flow units. The heat flow map of the area, such as it is, does not correlate well with other geophysical maps. This is in variance to the correlations found in other areas, as cited above. Perhaps the collection of additional data in this area will change this apparent contradiction. If not, it will give some indication of the general applicability of the methods.

VII. SUMMARY DISCUSSION

If HDR is to fully achieve its potential as a viable source of energy, methods of exploration for HDR must be evolved and successfully tested in various

Fig. 11.
Seismicity map of Arizona (modified
from Sumner, 1976).

Fig. 12.
Residual aeromagnetic map of Arizona
(modified from Sauk and Sumner, 1978).

Fig. 13.
Depth below sea level to base of the
magnetic crust (modified from Byerly
and Stolt, 1978).

Fig. 14.
Geothermal gradient (modified from
preliminary AAPG, 1974).

geologic provinces. It is probable that no one method will be sufficient, rather that several methods will be necessary for a successful program. Greater confidence will be provided by the correlation and reinforcement by various methods or approaches.

The "Aiken" or Aquarius prospect appears to have some of the general characteristics that a thermally enhanced region should have to warrant further investigation as a potential HDR prospect. Each of these various characteristics can be interpreted as an indication of thermal enhancement. When these characteristics are synthesized, the Aquarius prospect appears to have an above average probability of having high thermal potential.

The higher than normal thermal potential is suggested by several lines of evidence and inference. The tectonic situation of being an area of uplift and propinquity to several intersecting regional-scaled fracture systems as inferred from surface geology, aeromagnetic and gravity trends, is conducive to thermal enhancement by upward leakage of thermal fluids. Gravity lows like the Aquarius low are often found to be the result of the emplacement of silicic rocks having high thermal conductivity and high radioactive heat generation. The area of the prospect exhibits a seismic travel time delay and attenuation of seismic wave amplitudes, anomalous conditions that are usually explained by elevation of the isotherms in the crust. The elevation of the isotherms in the crust is also indicated by a shallow depth to the Curie point temperature.

The Aquarius prospect appears worthy of additional investigation such as detailed geologic mapping, heat flow measurements, and deep electrical soundings. This prospect may only be a type study because, although the probability is high that the area is thermally enhanced it does not have an insulating blanket of sedimentary rocks.

REFERENCES

1. J. Combs and L. J. P. Muffler, "Exploration for Geothermal Resources," in Geothermal Energy, P. Kruger and C. Otte, Eds. (Stanford University Press, Stanford, 1973) Chap. 5, pp. 93-128.
2. L. M. Libby and W. F. Libby, "Geographical Coincidence of High Heat Flow, High Seismicity, and Upwelling with Hydrocarbon Deposits, Phosphorites, Evaporites, and Uranium Ores," Proc. Nat. Acad. Sci. USA 71, 3935 (1974).

3. A. Beach, "The Interrelation of Fluid Transport, Deformation, Geochemistry and Heat Flow in Early Proterozoic Shear Zones in the Lewison Complex," *Philos. Trans. R. Soc. London* 280, 569-604 (1976).
4. C. L. V. Aiken, "Analysis of the Gravity Anomalies of Arizona", PhD. Dissertation, University of Arizona (1976).
5. R. A. Young and W. J. Brennan, "Peach Springs Tuff: Its Bearing on Structural Evolution of the Colorado Plateau and Development of Cenozoic Drainage in Mohave County, Arizona," *Geol. Soc. Am. Bull.* 85, 83-90 (1974).
6. V. Cermak, "Correlations of Heat Flow Values with the Tectonic Structure in Czechoslovakia," *Nature* 218, 556-557 (1968).
7. C. B. Richardson, "Cross Sections of Southern Arizona and Adjacent Parts of California," *Ariz. Geol. Soc. Dig.* 10, 1-5 (1976).
8. E. B. Mayo, "Lineament Tectonics and Some Ore Districts of the Southwest," *Trans. Am. Inst. Min. Eng.* 211, 1169-1175 (1958).
9. H. Drewes, "The Cordilleran Orogenic Belt Between Nevada and Chihuahua," *Geol. Soc. Am. Bull.* 89, 641-657 (1978).
10. R. B. Smith and M. L. Sbar, "Contemporary Tectonics and Seismicity of the Western United States with Emphasis on the Intermountain Seismic Belt," *Geol. Soc. Am. Bull.* 85, 1205-1218 (1974).
11. L. A. Warner, "The Colorado Lineament: A Middle Precambrian Wrench Fault System," *Geol. Soc. Am. Bull.* 89, 161-171 (1978).
12. M. D. Fuller, "Expression of E-W Fractures in Magnetic Surveys in Parts of the U.S.A.," *Geophysics* 29, 602-622 (1964).
13. W. R. Landwehr, "Belts of Major Mineralization in Western United States", *Econ. Geol.* 62, 494-501 (1967).
14. M. L. Silberman, B. R. Berger, and R. A. Koski, "K-Ar Age Relations of Granodiorite Emplacement and Tungsten and Gold Mineralization Near Getchell Mine, Humboldt, Nevada," *Econ. Geol.* 69, 646-656 (1974).
15. F. Goff, Los Alamos Scientific Laboratory, personal communication, August, 1978.
16. E. M. Shoemaker, R. L. Squires, and M. J. Abrams, "The Bright Angel and Mesa Butte Fault Systems of Northern Arizona," in *Geology of Ariz.*, Karlstrom et al., Eds., *Geol. Soc. Am. Mtng, Flagstaff, Ariz.* pp. 355-391 (1974).
17. J. G. Moore, "K/Na Ratio of Cenozoic Igneous Rocks of the Western United States," *Geochim. Cosmochim. Acta* 26, 101-130 (1962).
18. L. B. Isaacson and S.B. Smithson, "Gravity Anomalies and Granite Emplacement in West-Central Colorado," *Geol. Soc. Am. Bull.* 87, 22-28 (1976).

19. E. R. Decker and S. B. Smithson, "Heat Flow and Gravity Interpretation Across the Rio Grande Rift in Southern New Mexico and West Texas," J. Geophys. Res. 80, 2542-2551 (1975).
20. V. Cermak, "Heat Flow and Gravity in Czechoslovakia," Stud. Geophys. Geod. 16, 77-87 (1972).
21. F. X. Bostick, Jr. and H. W. Smith, "Investigation of Large-Scale Inhomogeneities in the Earth by the Magnetotelluric Method," Proc. IRE 40, 2339-2346 (1962).
22. J. S. Reitzel, D. I. Gough, H. Porath, and C. W. Anderson III, "Geomagnetic Deep Sounding and Upper Mantle Structure in the Western United States," Geophys. J. R. Astron. Soc. 19, 213-235 (1970).
23. U. Schmucker, "Anomalies of Geomagnetic Variations in the Southwestern United States," Monograph 13, Scripps Inst. Oceanography (1970).
24. H. Porath, D. W. Oldenburg, and D. I. Gough, "Separation of Magnetic Variation Fields and Conductive Structures in the Western United States," Geophys. J. R. Astron. Soc. 19, 237-260 (1970).
25. H. Porath and A. Dziewonski, "Crustal Electrical Conductivity Anomalies in the Great Plains Province of the United States," Geophysics 36, 382-395.
26. A. F. Kuckes, "Correspondence Between the Magnetotelluric and Field Penetration Depth Analyses for Measuring Electrical Conductivity," Geophys. J. R. Astron. Soc. 32, 381-385 (1973).
27. A. A. Kovtun, E. L. Kokvina, and A. A. Lipatov, "Magnetotelluric Field Above a Three-Dimensional Elevation of the Basement," Izv. Earth Phys. 8, 85-90 (1974).
28. B. Caner, W. H. Cannon, and C. E. Livingstone, "Geomagnetic Depth Sounding and Upper Mantle Structure in the Cordillera Region of Western North America," J. Geophys. Res. 72, 6335-6351 (1967).
29. R. E. Warren, J. G. Sclater, V. V. Vacquier, and R. F. Roy, "A Comparison of Terrestrial Heat Flow and Transient Geomagnetic Fluctuations in the Southwestern United States," Geophysics 34, 463-478 (1969).
30. G. Ye. Gugunava, and D. A. Kiknadze, "On the Relation between Geoelectric Structure and Temperature Distribution in the Upper Layers of the Earth," Izv. Earth Phys. 9, 98-100 (1975).
31. J. F. Hermance and L. R. Grillo, "Correlation of Magnetotelluric, Seismic and Temperature Data from Southwest Iceland," J. Geophys. Res. 75, 6582-6591 (1970).
32. T. R. Rikitake, "Electrical Conductivity Anomaly in the Earth's Crust and Mantle," Earth-Sci. Rev. 7, 35-65 (1971).

33. D. I. Gough, "The Geophysical Significance of Geomagnetic Variation Anomalies," *Phys. Earth Planet. Inter.* 7, 379-388 (1973).
34. L. L. Venyan, V. V. Borets, A. M. Lyapishev, B. Ye. Marderfeld, and A. V. Rodionov, "Deep Electromagnetic Investigations in the Soviet Far East," *Mod. Geol.* 5, 65-73 (1975).
35. B. Caner and W. H. Cannon, "Geomagnetic Depth-Sounding and Correlation with Other Geophysical Data in Western North America," *Nature* 207, 927-929.
36. B. Caner, "Electrical Conductivity Structure in Western Canada and Petrological Interpretation," *J. Geomagn., Geoelectr.* 22, 113-129 (1970).
37. T. Madden, "Goelectric Upper Mantle Anomalies in the United States," *J. Geomagn. Geoelectr.* 22, 91-95 (1970).
38. M. J. Berry, W. R. Jacoby, R. R. Niblett, and R. A. Stacey, "A Review of Geophysical Studies in the Canadian Cordillera," *Can. J. Earth Sci.* 8, 788-801 (1971).
39. L. K. Law and R. P. Riddihough, "A Geographical Relation Between Geomagnetic Variation Anomalies and Tectonics," *Can. J. Earth Sci.* 8, 1094-1105 (1971).
40. H. Porath, "Magnetic Variation Anomalies and Seismic Low-Velocity Zone in the Western United States," *J. Geophys. Res.* 76, 2643-2648 (1971).
41. P. A. Camfield, D. I. Gough, and H. Porath, "Magnetometer Array Studies in North-Western United States and South-Western Canada," *Geophys. J. R. Astron. Soc.* 22, 201-221 (1970).
42. J. H. DeBeer, D. I. Gough, and J. S. V. VanZig1, "An Electrical Conductivity Anomaly and Rifting in Southern Africa," *Nature* 225, 678-680 (1975).
43. R. E. M. Lilley, "Electrical Conductivity Anomalies and Continental Seismicity in Australia," *Nature* 257, 381-382 (1975).
44. G. D. Garland, "Correlation Between Electrical Conductivity and Other Geophysical Parameters," *Phys. Earth Planet. Inter.* 10, 220-230 (1975).
45. D. R. Word, H. W. Smith, and F. X. Bostick, Jr., "Crustal Investigations by Magnetotelluric Tensor Impedance Method," *Am. Geophys. Union Monograph* 14, 145-167 (1971).
46. G. V. Keller, "Electrical Studies of the Crust and Upper Mantle," *Am. Geophys. Union Monograph* 14, 107-125 (1971).
47. D. I. Gough, "Electrical Conductivity under Western North America in Relation to Heat Flow Seismology and Structure," *J. Geomagn. and Geoelectr.* 26, 105-123 (1974).

48. G. R. Jiracek, "Deep Electrical Resistivity Investigations Coupled with Dry Geothermal Reservoir Experiments in New Mexico," Tech. Prog. Rpt., University of New Mexico, 47 pp. (1975).
49. J. F. Hermance and L. R. Grillo, "Constraints on Temperatures Beneath Iceland from Magnetotelluric Data," Phys. Earth Planet. Inter. 8, 1-12 (1974).
50. L. Stegena, "Electric Conductivity Structure and Geothermal Reservoirs," Acta Geophys. Montanist. Acad. Sci. Hung. Tomus 11, 377-397 (1976).
51. O. L. Anderson, "The Role of Experimental Physical Acoustics in Geophysics," Tectonophysics 13, 521-540 (1972).
52. H. Kanomari, "Seismological Evidence for Heterogeneity of the Mantle," J. Geomagn. and Geoelectr. 22, 53-70 (1970).
53. A. L. Hales and H. A. Doyle, "P and S Travel Time Anomalies and Their Interpretation," Geophys. J. R. Astron. Soc. 13, 403-415 (1967).
54. D. J. Stuart, J. C. Roller, W. H. Jackson, and G. B. Mangan, "Seismic Propagation Paths, Regional Traveltimes, and Crustal Structure in the Western United States," Geophysics 29, 178-187 (1964).
55. A. L. Hales and E. Herrin, "Travel Times of Seismic Waves," in The Nature of the Solid Earth, E. C. Robertson, Ed. (McGraw-Hill Inc., New York, 1972, Chap. 8, pp. 172-215).
56. S. C. Solomon, "Seismic-Wave Attenuation and Partial Melting in the Upper Mantle of North America," J. Geophys. Res. 77, 1483-1502 (1972).
57. D. P. Hill, "Velocity Gradients in the Continental Crust from Head-Wave Amplitudes," Am. Geophys. Union Monograph 14, 71-75 (1971).
58. J. Jordan, R. Black, and C. C. Bates, "Patterns of Maximum Amplitudes of Pn and P Waves Over Regional and Continental Areas," Bull. Seis. Soc. Am. 55, 693-720 (1965).
59. J. S. Sumner, "Earthquakes in Arizona," Ariz. Bur. Mines Field Notes 6-1, 1-5 (1976).
60. W. A. Sauk and J. S. Sumner, "Residual Aeromagnetic Map of Arizona," University of Arizona Press, 1 sheet (1970).
61. B. K. Bhattacharyya and L. Lev, "Analysis of Magnetic Anomalies Over Yellowstone National Park: Mapping of Curie Point Isothermal Surface for Geothermal Reconnaissance," J. Geophys. Res. 80, 4461-4465 (1975).
62. P. E. Byerly and R. H. Stolt, "An Attempt to Define the Curie Point Isotherm in Northern and Central Arizona," Geophys. 42, 1394-1400 (1977).

63. R. T. Shuey, D. K. Schellinger, E. H. Johnson, and L. B. Alley, "Aeromagnetics and the Transition Between Colorado Plateau and Basin Range Provinces," *Geology* 1-3, 107-110 (1973).
 64. Am. Assoc. Petr. Geol., "Preliminary Geothermal Gradient Maps of the United States and Canada," (1974).
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